Jerolim ANDRIĆ, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia, jerolim.andric@fsb.hr
Stanislav KITAROVIĆ, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
Maja PLAVŠIĆ, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
Ana ŽARKO, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia

HULL GIRDER ULTIMATE STRENGTH OF A DAMAGED OIL TANKER

Abstract

Within the scope of the presented work a hull girder ultimate strength analyses of the double hull oil tanker structures damaged by the collision or grounding is performed. An incremental-iterative progressive collapse analysis method prescribed by the forthcoming IACS Harmonized Common Structural Rules (H-CSR) is used for determination of the ultimate (vertical) bending moments and collapse sequences of the considered structures. Three characteristic variants of the oil tanker main frame cross sections of a different geometry and size (Aframax, Suezmax and VLCC) are considered. The position of a ship's side and/or bottom damage is defined in accordance with the IACS H-CSR. Proposed analytical formulations of the relationship between reduction of the hull girder ultimate bending moment (with respect to the undamaged state) and damage size are based on the results of a systematic variation of a ship's side or bottom damage size. Finally, comparison of the collapse sequences determined for the undamaged and damaged state (defined by IACS H-CSR) of the considered structures is performed.

Key words: collision, damaged ships, hull girder ultimate strength, grounding, tanker structure

UZDUŽNA GRANIČNA ČVRSTOĆA OŠTEĆENOG TRUPA TANKERA

Sažetak

U radu su provedene analize uzdužne granične čvrstoće različitih konstrukcija trupa broda za prijevoz nafte s dvostrukom oplatom oštećenog sudarom i/ili nasukavanjem. Pri tome je za određivanje graničnih (vertikalnih) momenata savijanja i kolapsnih sekvenci razmatranih konstrukcija korištena inkrementalno-iterativna metoda analize progresivnog kolapsa propisana u okviru nadolazećih IACS harmoniziranih pravila (H-CSR). Razmatrane su tri karakteristične varijante poprečnog presjeka glavnog rebra trupa tankerskih konstrukcija različitih dimenzija i geometrije (Aframax, Suezmax i VLCC). Pozicija oštećenja boka i/ili dna broda definirana je u skladu s IACS H-CSR. Predložene analitičke formulacije ovisnosti smanjenja graničnog momenta savijanja trupa (u odnosu na neoštećeno stanje) o veličini i poziciji oštećenja određene su analizom rezultata sistematskog variranja veličine oštećenja boka ili dna broda. U konačnici su uspoređene kolapsne sekvence određene za neoštećeno i oštećeno stanje (prema zahtjevima IACS H-CSR).

Ključne riječi: granična čvrstoća trupa, nasukavanje, oštećeni brod, sudar, tankerska konstrukcija

1. Introduction

A large number of ship accidents resulting in a loss of cargo, pollution of the environment and a loss of human life still occur, despite the advancements in a ship design, production and navigation procedures. Accident scenarios typically include collision, grounding, fire and explosion. In that respect, it is of a great importance to ensure acceptable safety level for ships damaged in those accidents. When a ship is damaged, the ship operator's decisions regarding the salvage actions should be based on evaluation of the damage effects on the ships safety using the residual strength assessment procedure. Adequate hull girder strength in intact condition does not necessarily guarantee an acceptable safety margin in damaged conditions.

A draft of the IACS Harmonized Common Structural Rules (H-CSR) [1] has been released for the industry review in April 2013. In comparison to the IACS CSR currently in force [2], IACS H-CSR contains additional requirement regarding the residual strength of tankers and bulk carriers, i.e. the hull girder ultimate strength in prescribed damaged conditions. According to the IACS H-CSR, the residual strength is evaluated for the two specific accident scenarios: collision and grounding. A similar approach can be found in [3], which prescribes an additional requirement regarding the ultimate hull girder strength check for the damaged condition.

Among a number of the contemporary methods for the hull girder strength evaluation, various incremental-iterative progressive collapse analysis method based on Smith's approach [4] are arguably the most widespread. Furthermore, rules of many classification societies, including IACS CSR and IACS H-CSR, prescribe utilization of incremental-iterative procedures based on Smith's approach for evaluation of the longitudinal ultimate load-capacity of ship structures. Overview of various existing methods for the hull girder ultimate strength calculation in intact condition can be found in [5-9], while the critical review of their accuracy can be found in [10]. Recently, the residual hull girder strength has been investigated through two different approaches: nonlinear FEM, e.g. [11-13], and an incremental-iterative procedures based on Smith's approach [14-21].

Intention of the present study is to investigate the influence of the damage size on the ultimate hull girder capacity of oil tankers for the two characteristic types of accidents: collision and grounding. Proposed analytical formulations of the relationship between the reduction of the hull girder ultimate bending moment (with respect to the undamaged state) and damage size are based on the analysis of the results of a systematic variation of damage extent of ship's side or bottom.

2. Capacity models of considered hull girder structures

Three characteristic variants of the double hull oil tanker midship sections of a different geometry and size (Aframax, Suezmax and VLCC) are considered. All examined structures are designed according to the pre-CSR requirements of different classification societies. The main particulars of the tanker structures considered by this study are given in Table 1. Examined structures denoted as models M2 and M3 (Suezmax and VLCC tanker) belong to the standard set of the ISSC benchmark examples and all relevant data regarding their material and geometric properties are given in [7-8]. Figs. 1 to 3 illustrate one-bay structural models at midship section of all considered structures in intact condition. Structural model definition, essential for all ultimate bending capacity calculations performed by the coauthors for the purposes of the present paper is done using the MAESTRO [22] computer program. For all models no corrosion deduction has been implemented, so as-built scantlings were used for the study.

Table 1. Main particulars of the examined ships

	M1 - Aframax tanker	M2 - Suezmax tanker	M3 - VLCC tanker
L_{bp} (m)	235	265	320
B (m)	42	46.4	58
D (m)	21	23.2	30
C_B (-)	0.86	0.83	0.82

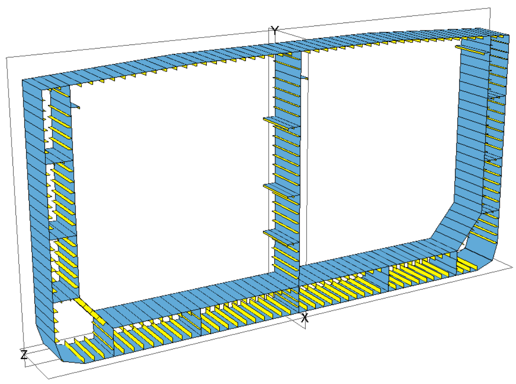


Fig. 1. One-bay model of the Aframax class double hull oil tanker midship section structure (model M1)

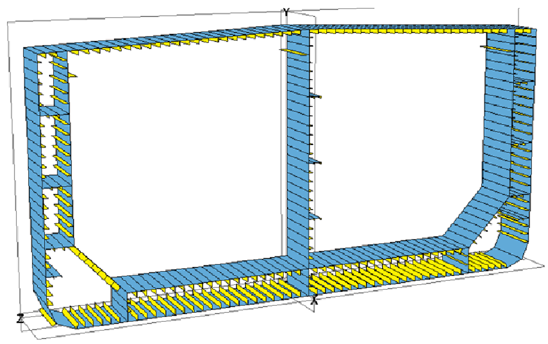


Fig. 2. One-bay model of the Suezmax class double hull oil tanker midship section structure (model M2)

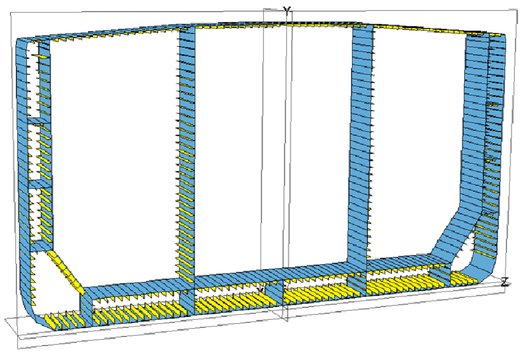
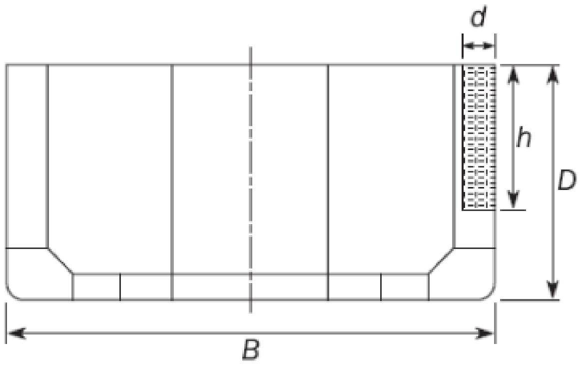


Fig. 3. One-bay model of the double hull VLCC midship section structure (model M3)

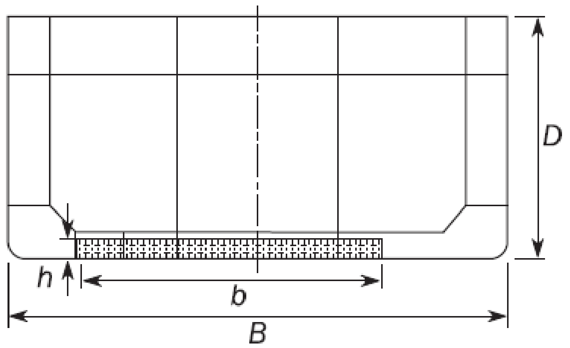
3. Damage scenarios

The damage due to grounding and collision are the most common reasons of the destruction of ship structures. Ship to ship collision causes the bow of the striking ship to collapse and the side of the struck ship to be damaged. It is the most destructive among all possible damages. Ship grounding on rock(s) results in a cutting or crushing of the bow bottom [15]. The basic definition of the damage extent in this study was performed according to [1] and a specified extent of damage for tanker structures for collision and grounding type of accident is illustrated by Figs. 4 and 5, respectively. The hull girder ultimate bending capacity with the specified damage extents is to be checked.



Damage penetration, in m	Side shell arrangement	
	Single side	Double side
Height, h	0.75 D	0.60 D
Depth, d	$B/16$	$B/16$

Fig. 4. Damage extent for collision specified by IACS H-CSR [1]



Damage penetration, in m	Bulk carriers	Oil tankers
Height, *h*	Min (*B* /20, 2)	Min (*B* /15, 2)
Breadth, *b*	0.60 *B*	0.60 *B*

Fig. 5. Damage extent for grounding specified by IACS H-CSR [1]

The performed systematic variation of a damage size is based on the following principles:

- For the <u>collision case</u> depth of the damage penetration is kept constant ($h=B/16$), as specified by the Rules, while the damage penetration height is systematically varied from $0.1D$ to $0.8D$, with the step of $0.1D$. For this case the damage is on one side only and located immediately below the freeboard deck;
- For the <u>grounding case</u> height of the damage penetration is kept constant ($h=\min[B/15, 2]$) as specified by the Rules, while the damage penetration breadth is systematically varied from $0.1B$ to $0.8B$, with the step of $0.1B$. For this case the damage is considered to be located symmetrically from the CL on PS and SB side.

Nine different models were generated for the each of three tankers (eight damaged and one intact) and used for each damage case. Several examples of a damaged ship models are presented in Figs. 6 and 7 for the collision and grounding case, respectively.

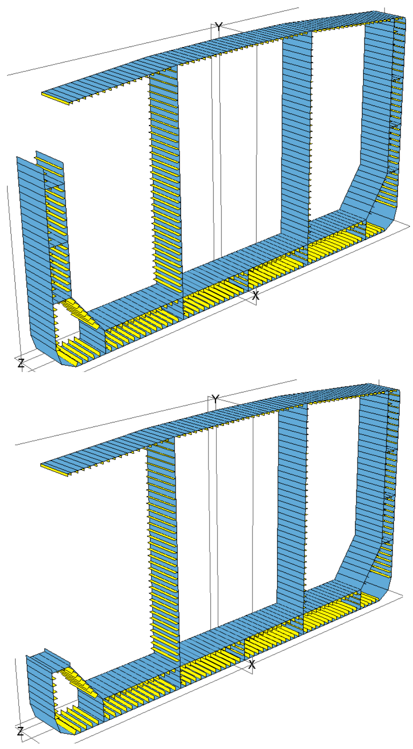


Fig. 6. One-bay model of the VLCC double hull oil tanker midship section (model M3), relevant for collision case with damage size of $0.2D$ and $0.7D$

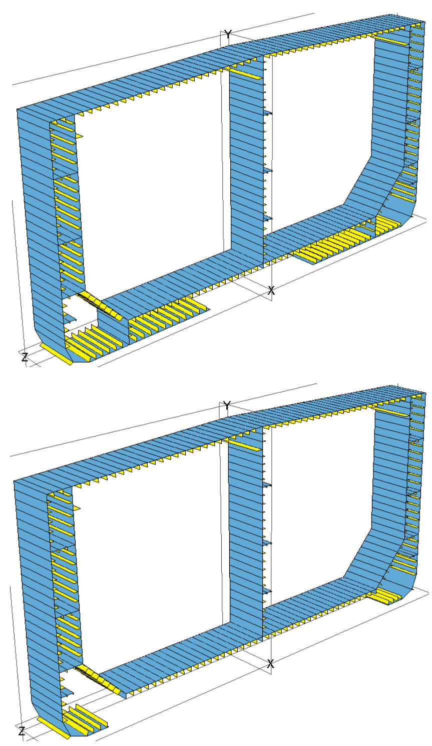


Fig. 7. One-bay model of the Suezmax double hull oil tanker midship section (model M2), relevant for grounding case with damage size of $0.3B$ and $0.8B$

4. Hull girder ultimate strength results

Imminent occurrence of the inter-frame collapse prior to any other feasible global collapse mode ensures that the global structural behavior of the complex monotonous thin-walled structures submitted to flexure can be idealized in accordance with the beam bending theory during the whole collapse process. This implication represents the fundamental premise of the Smith's method [4], which is considered to be the first among established progressive collapse analysis methods that incorporate more sophisticated consideration of the structural collapse sequence and structural post-critical response of structural elements. Development of the original method subsequently stimulated proposition of various methods based on Smith's approach (e.g. [23-25]). In shipbuilding practice, rules of many classification societies (and their associations [1-2]) prescribe utilization of the incremental-iterative procedures based on Smith's approach for evaluation of longitudinal ultimate capacity during the structural design synthesis. The vertical ultimate bending moment capacities of the hull girder transverse section, in hogging and sagging conditions, are defined as the maximum values of the curves of the vertical bending moment capacity versus the curvature χ of the transverse section considered. The curve is obtained through an incremental-iterative approach. Within the framework of this paper, IACS incremental-iterative progressive collapse analysis method is employed, as previously implemented within OCTOPUS [26] computer program. In performed calculations several assumptions were made:

- Calculation procedure for the vertical ultimate bending moment capacities of a damaged section is same as for the intact condition and follows recommendations given in [1-2];
- Damaged area, as defined in Chapter 3, carries no loads and is therefore removed from the models;
- Only vertical bending is considered. The effects of the shear force, torsion loading, horizontal bending moment and lateral pressure are neglected;
- The ultimate bending capacity of the damaged transverse cross section is calculated with the model kept in upright position and a neutral axis rotation is not considered (some recommendations regarding the inclusion of the neutral axis rotation is given in [18]);

In this study the residual strength index (*RIF*), originally introduced by Fang and Das in [27] and used by Hussein and Gudes Soares in [15], as a way to compare the ultimate strength capacity of the damaged hull ($M_{U,Damage}$) with the intact one ($M_{U,Intact}$), is used to systematically investigate the relationship between the ultimate strength capacity and a damage size:

$$RIF = \frac{M_{U,Damage}}{M_{U,Intact}} \tag{1}$$

Similar approach can be used to compare other relevant sectional characteristics (A, I_v, W_D, W_B) of the damaged and intact hull girder cross sections:

$$RIF\_A = \frac{A_{Damage}}{A_{Intact}};\; RIF\_I = \frac{I_{Damage}}{I_{Intact}};\; RIF\_W_D = \frac{W_{D,Damage}}{W_{D,Intact}};\; RIF\_W_B = \frac{W_{B,Damage}}{W_{B,Intact}} \tag{2}$$

where A_{Damage} and A_{Intact} are cross sectional area in damaged and intact condition, respectively; I_{Damage} and I_{Intact} are vertical moments of inertia for cross sections in damaged and intact condition, respectively; $W_{B,Damage}$ and $W_{B,Intact}$ are bottom sectional modulus in damaged and intact condition, respectively; $W_{D,Damage}$ and $W_{D,Intact}$ are deck sectional modulus in damaged and intact condition, respectively.

4.1. Grounding case

Summary of the obtained results for the grounding case is given in Table 2.

Table 2. Residual strength index for grounding

Damage ratio:	**M1-Aframax tanker**					
$\lambda=B_{damaged}/B$	*RIF_M-sagg*	*RIF_M-hogg*	*RIF_A*	*RIF_I*	*RIF_W*$_D$	*RIF_W*$_B$
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.988	0.966	0.973	0.969	0.988	0.992
0.2	0.977	0.934	0.952	0.942	0.976	0.983
0.3	0.966	0.907	0.931	0.914	0.964	0.975
0.4	0.951	0.867	0.907	0.881	0.949	0.938
0.5	0.933	0.829	0.877	0.839	0.929	0.864
0.6 (specified by H-CSR)	**0.910**	**0.789**	**0.853**	**0.802**	**0.910**	**0.804**
0.7	0.891	0.760	0.833	0.768	0.892	0.752
0.8	0.859	0.713	0.800	0.713	0.862	0.671
M2-Suezmax tanker						
$\lambda=B_{damaged}/B$	*RIF_M-sagg*	*RIF_M-hogg*	*RIF_A*	*RIF_I*	*RIF_W*$_D$	*RIF_W*$_B$
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.991	0.975	0.977	0.972	0.989	0.950
0.2	0.980	0.947	0.955	0.944	0.977	0.902
0.3	0.968	0.912	0.931	0.911	0.963	0.849
0.4	0.953	0.873	0.906	0.876	0.947	0.795
0.5	0.937	0.830	0.882	0.838	0.929	0.740
0.6 (specified by H-CSR)	**0.922**	**0.797**	**0.860**	**0.803**	**0.912**	**0.692**
0.7	0.902	0.757	0.838	0.766	0.892	0.643
0.8	0.874	0.707	0.807	0.714	0.864	0.578
M3-VLCC tanker						
$\lambda=B_{damaged}/B$	*RIF_M-sagg*	*RIF_M-hogg*	*RIF_A*	*RIF_I*	*RIF_W*$_D$	*RIF_W*$_B$
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.987	0.967	0.977	0.974	0.989	0.952
0.2	0.976	0.941	0.956	0.947	0.977	0.906
0.3	0.964	0.912	0.935	0.919	0.964	0.861
0.4	0.950	0.879	0.910	0.886	0.948	0.808
0.5	0.935	0.849	0.889	0.856	0.934	0.762
0.6 (specified by H-CSR)	**0.920**	**0.823**	**0.870**	**0.827**	**0.919**	**0.722**
0.7	0.899	0.792	0.850	0.794	0.901	0.677
0.8	0.876	0.757	0.824	0.754	0.879	0.624

Damage ratio λ for grounding has been specified as breadth of damage area (B_{damage}) divided by the breadth of the ship (B), see Table 2.

From the presented results it can be noted that the reduction of the hull girder ultimate bending moment, expressed through the *RIF*, is larger in the hogging than in the sagging case for all evaluated tankers. Data given in Table 2 enable easy establishment of the dependence between the reduction of the cross sectional characteristics (*RIF-A*, *I*, W_B, W_D) and *RIF*.

For example, a damage size ratio of λ=0.6 in the grounding case (specified by the IACS H-CSR as the requested damage value), cause average reduction of the cross section area by 13.9%. At the same time, the ultimate hogging and sagging moments are reduced in average (for all three models) by 19.7% and 8.3%, respectively.

Graphical presentation of the relationship between *RIF* and a damage size ratio is presented in Fig. 8.

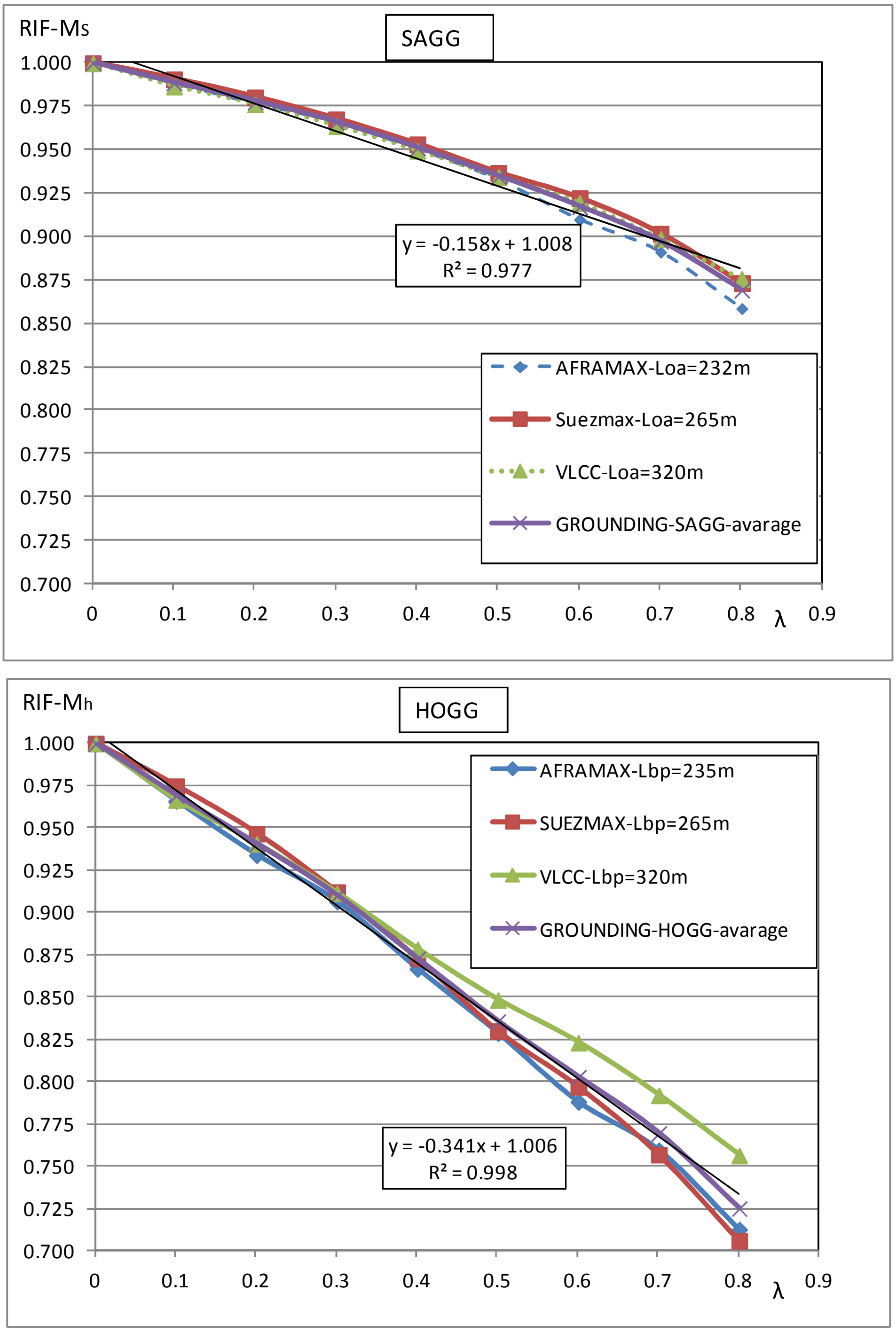


Fig. 8. *RIF* for grounding in hogging and sagging cases

From the data presented in Table 2 and Fig. 8, a linear equations are proposed to describe the relationship between the *RIF* and a damage size ratio ($\lambda = B_{damage}/B$):

$$RIF_{grounding-SAGG} = 1.008 - 0.158\lambda \tag{3}$$

$$RIF_{grounding-HOGG} = 1.006 - 0.341\lambda \tag{4}$$

Hussein and Guedes Soares published [15] a similar research and specified a unique expression for the double hull oil tanker structure:

$$RIF_{grounding-HOGG} = 1.02 - 0.254\lambda \tag{5}$$

Collapse sequences in hogging and sagging are analyzed in detail for undamaged and damaged case ($\lambda = 0.6$) for all three examined cross sections. Vertical bending moment capacity versus the curvature χ curve is presented for the undamaged and damaged conditions for the Aframax tanker model in hogging, see Fig. 9, as an example.

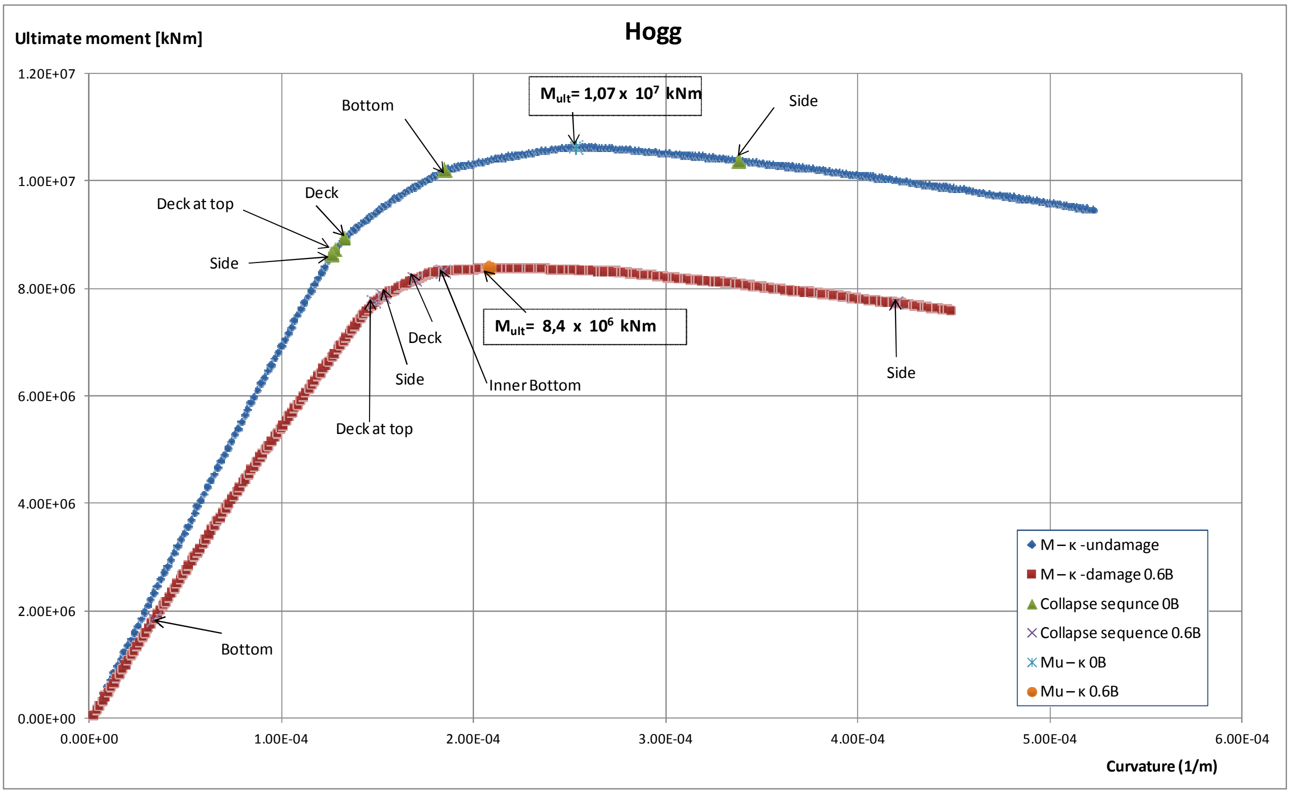


Fig. 9. Collapse sequences of Aframax tanker in grounding, hogging case

Due to the reduced cross section, it can be noted that the damaged section has reduced bending stiffness and reaches the ultimate bending capability faster that the undamaged section. Also, the damaged section reaches the ultimate bending capacity at the lower curvature compared to the undamaged section.

Due to the ineffectiveness of the damaged bottom plating, which does not contribute to the bending stiffness of the cross section, the inner bottom plating is imposed with the higher compressive load. When inner bottom structure collapses due to buckling, the damaged section reaches the ultimate bending capacity. It can be noted that the undamaged section reached its ultimate bending capacity just after the bottom plating collapsed, but without the collapse of the inner bottom plating. Furthermore, it can be also noticed that the deck structure is the structural part that collapses first, due to the high tensile stresses in both cases.

In-house software [26] used in this study enables identification of the characteristic structural collapse sequence accounting for the load-shedding effect during the progressive load incrementation. This capability can enable determination of a more rational distributions of the longitudinally effective material within the process of concept design synthesis, i.e. during the consideration of various topologic variants and/or materially-geometrical properties of the feasible structural cross-sections, since it can point to the more efficient ways of required structural safety level accomplishment. Furthermore, collapse sequence can also be considered as a rational pathfinder during the material reduction process of the initially over-dimensioned cross section (for the case of structural safety criteria over-satisfaction).

4.2. Collision case

Summary of the obtained results for the collision case are given in Table 3.

Damage ratio λ for the collision is specified as the depth of the damage area (D_{damage}) divided by the depth of the ship (D), see Table 3.

Table 3. Residual strength indices for collision

Damage ratio:	**M1-Aframax tanker**					
$\lambda=D_{damaged}/D$	*RIF_M-sagg*	*RIF_M-hogg*	*RIF_A*	*RIF_I*	RIF_W_D	RIF_W_B
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.925	0.951	0.973	0.948	0.896	0.978
0.2	0.895	0.932	0.958	0.928	0.898	0.978
0.3	0.848	0.907	0.936	0.911	0.869	0.979
0.4	0.827	0.894	0.921	0.905	0.857	0.982
0.5	0.810	0.882	0.902	0.902	0.849	0.987
0.6 (specified by H-CSR)	**0.802**	**0.874**	**0.879**	**0.901**	**0.846**	**0.990**
0.7	0.802	0.873	0.861	0.901	0.847	0.988
0.8	0.803	0.872	0.836	0.897	0.850	0.974
M2-Suezmax tanker						
$\lambda=D_{damaged}/D$	*RIF_M-sagg*	*RIF_M-hogg*	*RIF_A*	*RIF_I*	RIF_W_D	RIF_W_B
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.931	0.959	0.975	0.953	0.929	0.987
0.2	0.897	0.937	0.960	0.935	0.902	0.984
0.3	0.856	0.910	0.939	0.920	0.877	0.986
0.4	0.837	0.895	0.922	0.914	0.865	0.989
0.5	0.826	0.882	0.903	0.912	0.859	0.994
0.6 (specified by H-CSR)	**0.820**	**0.873**	**0.885**	**0.912**	**0.858**	**0.996**
0.7	0.820	0.869	0.862	0.911	0.859	0.990
0.8	0.821	0.869	0.852	0.909	0.861	0.983
M3-VLCC tanker						
$\lambda=D_{damaged}/D$	*RIF_M-sagg*	*RIF_M-hogg*	*RIF_A*	*RIF_I*	RIF_W_D	RIF_W_B
0	1.000	1.000	1.000	1.000	1.000	1.000
0.1	0.934	0.957	0.975	0.949	0.928	0.981
0.2	0.896	0.935	0.960	0.929	0.899	0.977
0.3	0.860	0.917	0.942	0.915	0.876	0.978
0.4	0.834	0.903	0.926	0.908	0.864	0.981
0.5	0.818	0.892	0.906	0.905	0.857	0.986
0.6 (specified by H-CSR)	**0.813**	**0.888**	**0.891**	**0.904**	**0.855**	**0.988**
0.7	0.811	0.887	0.873	0.904	0.856	0.986
0.8	0.812	0.886	0.853	0.767	0.857	0.976

From the presented results it can be noted that the reduction of the hull girder ultimate bending moment expressed through residual *RIF* is larger in sagging than in hogging case for all evaluated tankers. This is the opposite trend with respect to the findings obtained for the grounding case.

Case with damage size ratio of λ=0.6 (specified by the IACS H-CSR as requested damage value), causes an average reduction of the cross sectional area by 11.5%. At the same time, the ultimate hogging and sagging moments are reduced in average (for all three models) by 12.2% and 18.8%, respectively.

Graphical presentation of the relationship between the *RIF* and a damage size ratio is presented in Fig. 10.

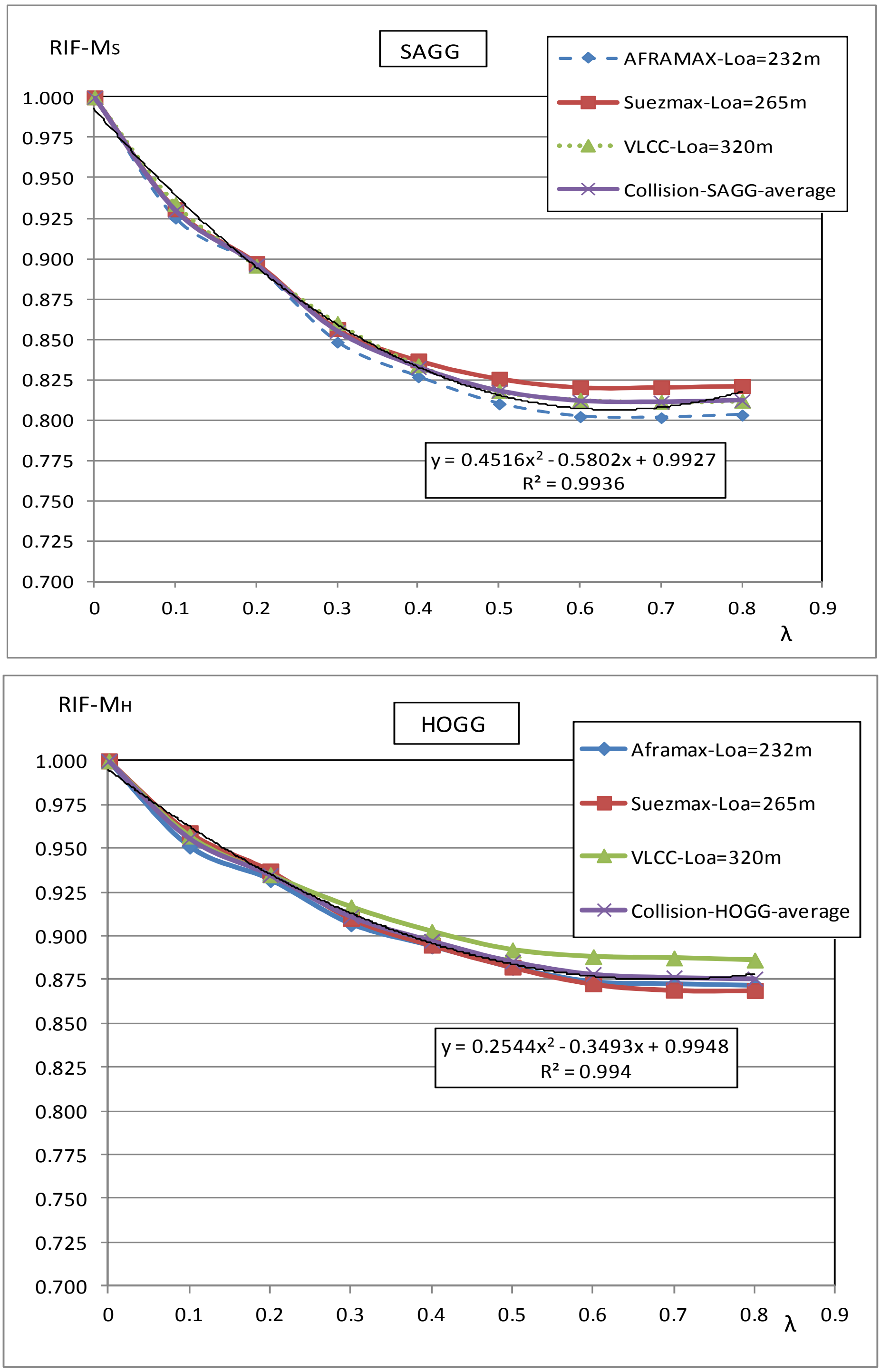


Fig. 10. *RIF* for collision in hogging and sagging case

From the data presented in Table 3 and Fig. 10, a linear equations can be used to represent the relationship between the *RIF* and a damage size ratio ($\lambda = D_{damage}/D$):

$$RIF_{collision-SAGG} = 0.9927 - 0.5802\lambda + 0.4516\lambda^2 \quad (6)$$

$$RIF_{collision-HOGG} = 0.9948 - 0.3494\lambda + 0.2544\lambda^2 \quad (7)$$

In [15], Hussein and Guedes Soares proposed a unique expression for the double hull oil tankers:

$$RIF_{collision} = 0.98 - 0.084\lambda \tag{8}$$

Collapse sequences in hogging and sagging are analyzed in detail for the undamaged and damaged cases (λ=0.6), for all three examined cross sections. Vertical bending moment capacity versus the curvature χ curves are presented for the undamaged and damaged conditions for Aframax tanker model in sagging, see Fig. 11, as an example.

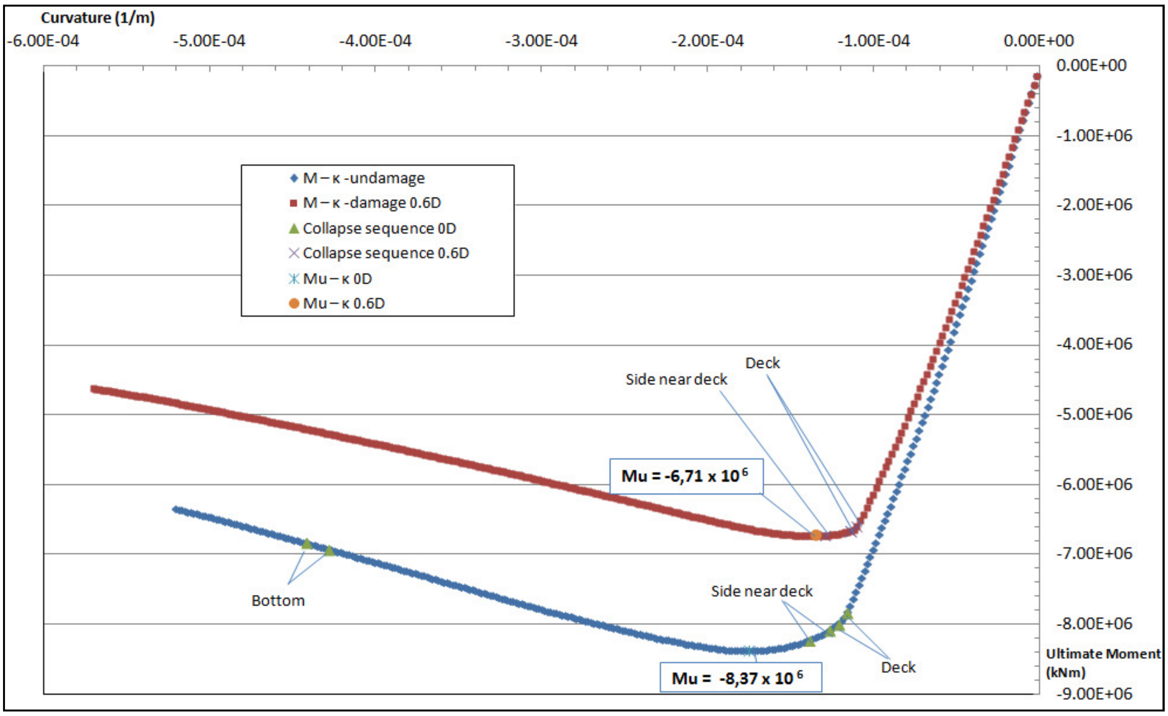


Fig. 11. Collapse sequences of Aframax tanker in collision, sagging case

A similar collapse sequences are identified for the damaged and undamaged conditions in the hogging and sagging case. The critical structural part which collapses first is the deck and after the part of the side structure (outer and inner) collapsed, the cross section reached its ultimate bending moment capacity.

5. Conclusions

Intention of the present study was to investigate the influence of the damage size on the ultimate hull girder capacity of the oil tankers for the two characteristic types of accidents: collision and grounding, using an IACS incremental-iterative progressive collapse analysis method.

Proposed analytical formulations of the relationship between reductions of the hull girder ultimate bending moment (with respect to the undamaged state) and a damage size ratio are based on the analysis of the results of a systematic variation of damage extent of ship's side or bottom.

In-house software used in this study enables identification of the characteristic structural collapse sequence and can be used for determination of more rational distributions of the longitudinally effective material within the design process.

Future investigation will go a step further with respect to the extension of the employed progressive collapse analysis method regarding the possibility to calculate vertical and horizontal ultimate bending moments and to enable rotation of the cross sectional neutral axis in damaged conditions.

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